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CERTIFICATION OF LIGHTNING PROTECTION FOR A FULL-AUTHORITY DIGITAL ENGINE CONTROL

M. Dargi, E. Rupke, K. Wiles
Lightning Technologies, Inc., USA

1.0 INTRODUCTION

As discussed in "Design of Lightning Protection for a Full-Authority Digital Engine Control" [1], FADEC systems present many challenges to the lightning protection engineer. In addition, verification of the protection-design adequacy for certification purposes presents additional challenges. In particular, close coordination between the airframe manufacturer and the suppliers of systems and subsystems is required.

The basic requirement of the certification plan of a FADEC system is to demonstrate compliance with Federal Airworthiness Regulations (FAR) 25.1309 [2] and 25.581. Certain FAR Issue Papers may be applicable and the forthcoming FAR 25.1315 [3] will clarify some ambiguities in the FARs pertaining to lightning protection of flight-critical and essential systems. These FARs are intended for transport aircraft, but there are equivalent sections for general aviation aircraft, normal and transport rotorcraft. Military aircraft may have additional requirements.

The criteria for demonstration of adequate lightning protection for a FADEC system includes the procedures outlined in Federal Aviation Administration (FAA) Advisory Circular (AC) 20-136 "Protection of aircraft electrical/electronic systems against the indirect effects of lightning." [4] As FADEC systems, including the interconnecting wiring, are generally not susceptible to direct attachment of lightning currents, this paper deals primarily with the verification of protection against indirect effects.

It is the responsibility of the airframe manufacturer or system integrator to provide the overall assurance of adequate lightning protection. However, it is often the case that the airframer's certification plan will refer to test or analysis plans conducted by system suppliers.

2.0 VERIFICATION METHODS

Verification of protection against lightning indirect effects is accomplished by the following procedures:

1. Demonstrating that actual transient levels in the interconnecting wiring do not exceed the established TCLs for the wiring.
2. Demonstrating that the individual equipment will tolerate the ETDLs without component damage.
3. Demonstrating that interconnected and operating systems will tolerate the applicable ETDLs (as applied to the cables of an interconnected system) without component damage or system functional upset.

The accepted methods of verification are through similarity of design with existing systems or aircraft, mathematical analysis or through simulated lightning testing.

2.1 SIMILARITY

Verification by similarity must be demonstrated by detailed comparisons of drawings, parts lists, system operating parameters and installation details. The certification plan must show that the FADEC systems, and the portions of the airframe which contain the systems, are identical to a previously certified system from a lightning-protection standpoint. Most importantly, the certification plan must show that TCLs, ETDLs and margins will remain similar. As FADEC systems are relatively new to the transport aircraft market and because of the rapidly developing technology of electronic control systems, certification entirely through similarity is rare.

2.2 ANALYSIS

Mathematical analysis is often used in the development stages of an aircraft, before prototypes are available, to determine the levels of lightning-induced transients that may be expected. For certification purposes, the use of "acceptable" mathematical analysis is often limited to certification documents describing lightning protection for small engineering changes. More frequently, analysis is used in conjunction with one or both of the other forms of verification. A common example is the extrapolation of the effects of high current from the results of a low-current test. Analysis should always include the worst-case scenario. Generally, verification by analysis will require significantly higher margins between TCL and ETDL than other forms.

2.3 TESTING

Conceptually it would be best to perform full-threat testing on fully configured and operational aircraft, performed either on a Go/No-Go basis or with a measurement and analysis scheme. This is seldom practical, however, primarily because of the cost and complexity of the required test equipment, test specimen and test facility. Therefore, to determine the indirect-effects protection of a FADEC system, testing will usually consist of two general categories of simulations: aircraft-level tests such as lightning transient analysis (LTA), used to determine the TCLs in the airframe or major sections of the airframe, and ETDL tests, performed with FADEC system components installed in the airframe. The second main category consists of a variety of bench tests performed on system components to assess protection against damage and functional upset.

2.4 TCL VERIFICATION

Verification of TCL will be accomplished by one of the following methods:

- Performance of a full-vehicle lightning test, in which reduced-scale pulses of current with waveforms of components A and H are circulated through the aircraft and measurements are made of actual transients induced in typical individual conductors and bulk cables associated

with the flight critical/essential systems. The measured transients are then extrapolated linearly to predict the levels that would be induced by full-threat component A and H currents. This procedure is also known as an LTA test. Measurements are made on representative circuits/cables, in accordance with a detailed test plan.

• Computation of anticipated actual transient waveforms/levels in representative wires/cables by analysis based on first principles (laws of electromagnetic effects, aircraft material properties and geometry). The analytical techniques utilized are verified by comparison with available prior test data.

• A combination of both of the above procedures. The extent to which each method will be employed will be detailed in test and/or analysis plans, to be submitted to airworthiness certifying authorities for approval.

2.5 ETDL VERIFICATION

Verification of compliance with the ETDLs specified is to be accomplished by tests conducted by the system or equipment vendors in accordance with test plans to be submitted by them to the airframe manufacturer for approval. Two test methods will be employed, as follows:

• Pin-injection tests in which full-scale voltage/current transients are applied (in most cases) between individual pins and case ground to verify circuit board component tolerance of the specified ETDLs.

• Bulk-cable tests, in which the specified cable ETDLs (bulk-cable currents) are transformer coupled or directly injected into interconnecting cables, with the system powered up and operating. The primary purpose of these tests is to verify that the system does not upset, although the test also verifies protection against system-related damage effects.

3.0 CERTIFICATION PLAN FOR A ROTORCRAFT FADEC/ENGINE SYSTEM

The following example of a certification plan for a hypothetical system provides detailed procedures applicable to most FADEC applications. This example addresses specifics for a rotorcraft FADEC/engine system, designated LTI-1000, including an Electronic Control Unit (ECU) and a Hydromechanical Control Unit (HMU). However, the general procedures and steps would be applicable for fixed-wing aircraft installation of the same or similar engine system, though changes in some of the ETDLs and TCLs may be necessary. The certification plan would begin with several brief introductory sections describing the purpose and citing the specific FAA and DoD requirements relevant to the rotorcraft. Our example begins after the opening paragraphs:

3.1 INTRODUCTION

- provide an overview of the system and application.

3.2 PURPOSE

- state goals of certification plan.

3.3 REQUIREMENTS

- cite specific FARS, ACs, MIL-STDs and issue papers as applicable.

3.4 LIGHTNING CRITERIA

The lightning environment which the helicopter (or fixed-wing aircraft) must withstand is defined in Appendix III of AC 20-136 [4] and Section 3.3 of MIL-STD-1795. [5]

These references define the same lightning environment, which is represented by current components A through D, a multiple-stroke arrangement of components A and D/2, and a multiple-burst environment. These components are fully defined in the aforementioned references and will not be described further here. They represent the characteristics of lightning-stroke currents entering, flowing through and exiting from an aircraft.

Applicability of individual components of the lightning environment to specific airframe surfaces or structures depends on the lightning strike zones of such surfaces/structures. Zone definitions are also found in AC 20-136 [4] and MIL-STD-1795A. [5]

3.5 STEPS IN DESIGN AND VERIFICATION

This section describes the steps being followed in design and verification of lightning protection for the LTI-1000 electronic control system. The steps described herein are similar to those in Section 7 of FAA AC 20-136 [4] (Steps a through g). Several of the steps include performance of tests. Plans for these tests are provided in separate documents, referenced herein.

3.5.1 Step a - Locate the lightning-strike zones

The LTI-1000 engine installed in the helicopter is not susceptible to direct lightning strikes. Instead, they are subject to lightning strikes conducted on and off the engine via the drive shaft, engine mounts, electrical wiring harnesses, fuel and drain lines. Systems and components exposed to such conducted currents are in zone 3, see Figure 1.

3.5.2 Step b - Establish the external environment for the zones

The external environment components applicable to specific zones are found in Appendix III of AC 20-136 [4], reproduced herein as Table 1.

Table 1 - Zonal Application of the External Environment for Determination of Indirect Effects

Zone	Current Waveforms					
	A	B	C	D	Multiple Burst	Multiple Stroke
1A	X	X			X	X
1B	X	X	X	X	X	X
2A		X		X	X	X
2B		X	X	X	X	X
3	X	X	X	X	X	X

Note: Indirect effects resulting from components B and C are usually insignificant.

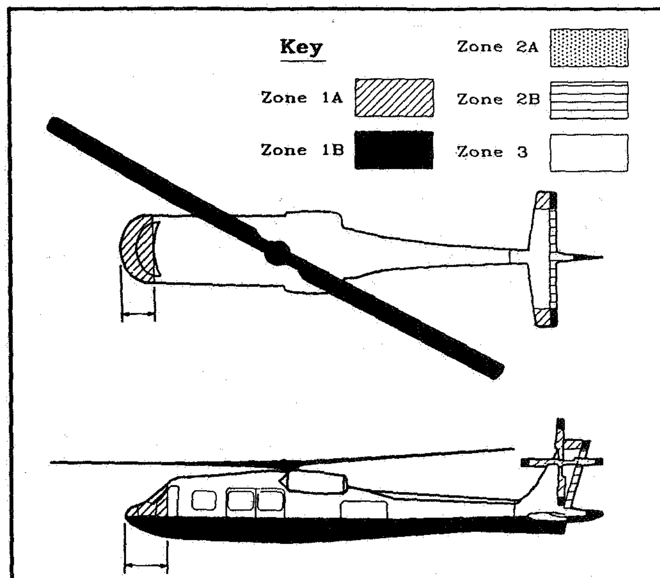

FIGURE 1 Strike zones for helicopters

Since components B and C produce insignificant indirect effects and the effects of component D are exceeded by those of component A, the LTI-1000 electronic control system is being designed to tolerate the indirect effects of current component A and the multiple-stroke and multiple-burst environments being conducted through the airframe. Since the LTI-1000 will be employed in a helicopter, the zone 3 currents will be conducted into the engine via the main rotor shaft, gearbox and engine output shaft. Lightning current will exit the engine via all other electrically continuous paths between the engine and the airframe.

3.5.3 Step c - Establish the internal environment

The internal lightning environment consists of lightning currents conducted into and out of the engine via the aforementioned conductive paths. The amount of lightning current that may flow in each path cannot be determined exactly by analysis, due to the complexity of the airframe and engine installation design and difficulty of quantifying electrical impedances associated with mechanical parts. However, gross estimates can be made of current magnitudes and, if simplifying assumptions are made on a worst-case basis, the resulting magnitudes will be higher than those actually experienced.

3.5.3.1 Lightning-current flow paths

3.5.3.1.1 Current entering engine

Nearly all lightning strikes to a helicopter enter the main rotor and exit from one or more of the lower extremities such as landing gear, skids, or tail boom. The lightning current path to an engine is illustrated basically in Figure 2.

Figure 2 shows a single-engine installation. In this figure, the following simplifications have been made, which result in the percentage of current entering the engine being higher than is actually expected to occur.

Simplifying Assumptions

- Current paths through rotor pitch control rods are omitted.
- 100% of external lightning current is expected to enter main bearing assembly.
- 50% of lightning current is assumed to flow through main bearing to output shaft(s), even though other low-impedance paths exist to the airframe via the mechanical-load paths (thrust amounts) and a variety of control and sensor paths.
- A single engine and output shaft is assumed. Twin output shafts would share the engine current, resulting in less current to each engine.

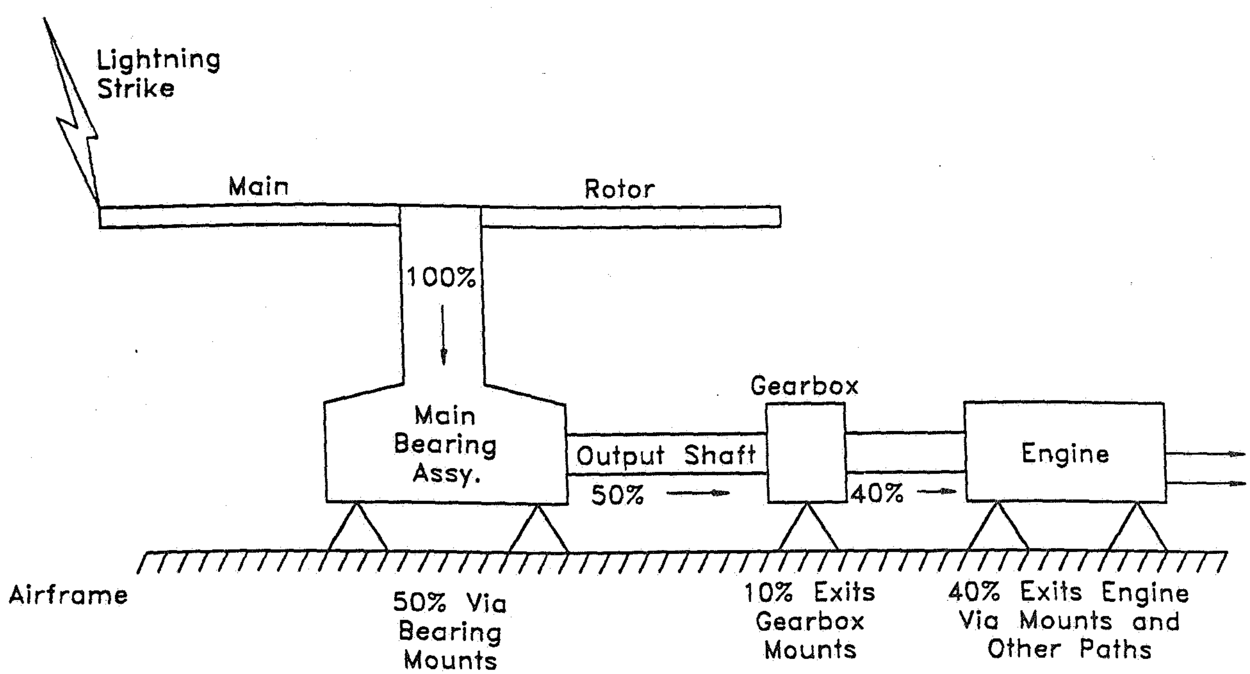

FIGURE 2 Basic lightning current paths to engine in rotor craft applications
• assumed lightning current distributions

Thus, the percentages of lightning current assumed to flow into the gearbox (50%) and engine (40%) are higher than actual, though the amount of margin cannot be determined.

Accordingly, it is assumed that 40% of the applicable full-threat, external lightning-current components, (components A, D/2, and H) will enter the engine via its output shaft and exit the engine via the engine mounts and other available paths. These current magnitudes are listed in Table 2.

Table 2 - Lightning Currents Entering Engine

Current Component	Peak Current
A	80 kA
D/2	20 kA
H	4 kA

The currents of Table 2 represent the internal lightning environment applicable to the LTI-1000 engine.

3.5.3.1.2 Currents exiting engine

The lightning current that entered the engine via its output shaft will exit from the engine via a variety of conductive paths. These are listed in Table 3.

Table 3 - Current Exit Paths from Engine Path

Path	No.
• Engine and gearbox mounting struts	7
• Exhaust duct	1
• Common drain	1
• Plenum drains	2
• Fuel hose	1
• Engine starter harness grounds	1
• ECS wiring harness	2
• Ground strap	1
Total number of paths:	16

If the current divided evenly, approximately 5 kA would flow from the engine to the airframe via each path. Actually, the magnitude of current in each path is determined by its impedance as compared with the impedances of other paths, with the highest currents flowing in the lowest impedance paths. The shortest, most direct paths to the airframe will have the lowest impedance and the highest current. These include the gearbox and engine-mount struts.

The metal cross sections and other aspects of the struts and other mechanical paths are fully capable of conducting their share of the lightning currents and no further considerations will be given to them in this plan.

It is necessary to establish the peak amplitudes of lightning currents flowing in the shields of ECS wiring harness as these become part of the TCL and ETDL specifications. For protection design purposes, it is assumed that current is shared equally among all exit paths and that ECS shield currents are as shown in Table 4.

Table 4 - ECS Harness Shield Currents (engine-to-airframe)

Current Component	Peak Current
A	5 kA
D/2	1.25 kA
H	0.25 kA

The fact that the ECS shield currents do not, in fact, exceed the levels of Table 4 will be verified by test of an engine in a simulated helicopter installation, as described in Section 3.5.7 (step g).

3.5.4 Step d - Identify the flight-critical/essential systems

The LTI-1000 ECS is assumed to be flight-critical as the engine is being certified for single- as well as twin-engine applications. All components of this system, including the ECU, engine-mounted accessories and interconnecting wiring harness are assumed to be flight-critical.

The ECS is exposed only to lightning indirect-strike effects in accordance with its zone 3 installation. The engine and ECS are protected from direct lightning strikes by the main rotor and the engine cowling, which are above the engine.

3.5.5 Step e - Establish transient control and design levels

The ETDLs represent the amplitude(s) of voltage(s) and/or current(s) that the ECS equipment is required to tolerate and remain operational without damage or system-functional upset. These levels are set higher than the maximum amplitude of transients that are allowed to be induced in interconnecting wiring and appear at equipment interfaces, which are the TCLs. The relationship between TCLs and ETDLs is illustrated in Figure 3. The ETDL is part of the specifications for the ECS electrical/electronic components. TCLs and ETDLs are defined in terms of the open circuit voltage (Voc) and the short circuit current (isc) appearing at wiring/equipment interfaces, and the currents in the shields of ECS interconnecting wiring harness. The "V" and "i" will be related by the source impedances (i.e., loop impedance) of interconnecting wiring, and different levels have been established for signal circuits and 28 VDC power circuits. The waveforms/levels defined in Appendix IV of FAA AC 20-136 [4] have been utilized to establish TCLs and EDTLs for cable shields and connector interfaces.

The equipment transient susceptibility level, also shown on Figure 3, is the amplitude of voltage or current which, when applied to the equipment, would result in damage to components or upset such that the equipment can no longer perform its intended function. This level is higher than the ETDL, and is not specified.

The TCLs and ETDLs for the single-engine helicopter installation are defined as individual connector pin-to-case (Voc) and

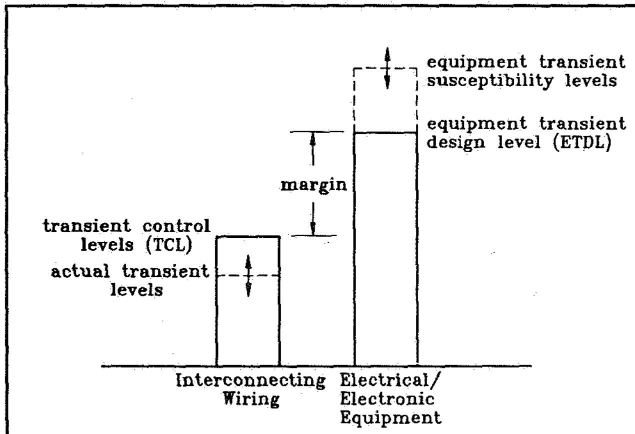

FIGURE 3 Relationships between transient levels

current (isc) waveforms and levels, as this condition is where the highest levels of induced effects are expected to appear in the helicopter circuits. This is the manner in which verification tests of equipment will be performed, as described in 3.5.7 (step g).

For design and verification of protection against system upset, a bulk-cable current is also defined. This represents the total voltage and/or current that can be induced in the loop formed between a complete cable shield and the adjacent engine or airframe. For overbraid shielded cables, or cables comprised entirely of individually shielded pairs, this is defined as a bulk-cable current. For verification test purposes, the levels will be directly injected or transformer coupled into the interconnecting cable while the system is powered up and operating, for the purpose of verifying protection against system-related damage and upset, as described briefly in section 3.5.7 (step g) and the referenced test plans.

All of the ETDLs are defined in the multiple-stroke mode, as defined in AC 20-136 [4] (one full-amplitude transient corresponding to the first return stroke, Component A, followed by twenty-three transients corresponding to subsequent strokes, Component D/2).

Specific TCLs and ETDLs established for the interconnecting wiring and electrical/electronic components are shown in Table 5.

Notes: 1. Waveforms and levels are defined in FAA AC 20-136 [4], Appendix IV.

2. Short-circuit current specification (isc) may be reduced from the level defined in AC 20-136 [4] if line-to-case ground impedance at airframe or engine-mounted accessory is determined to be greater than the impedance (5 ohms or 25 ohms) implied in the definition. In no case may the isc level be less than that produced by a 100-ohm impedance. If the isc specification is reduced in this manner, the ability of the remote interface to withstand the specified ETDL must be verified by transient test.

3. The specified shield-current amplitude is the current at the ECU interface (connectors E1, E2 and E3). Currents in branches of intra-engine harness shields will be lower. The total of currents in each branch will equal the specified current at the ECU connector.

4. The short-circuit (isc) current is as specified and may not be reduced as described in Note 2.

The transient levels presented in Table 5 represent a margin of 2:1 or greater between ETDLs and associated TCLs, in accordance with advice given in Section 9 of FAA AC 20-136. The TCL selections are intended to encompass the actual transient levels (ATLs) of the shielded conductors, and are generally based on an assumed harness-shield transfer impedance of 0.05 volt of conductor voltage per amp of shield current; a value typical of short-length shielded harness, such as employed between the ECU and other engine-mounted accessories. Thus, if the shield-harness TCL is 5 kA as listed in Table 5, the conductor voltage, Vc would be,

$$Vc = (0.05\ V/A)\ (5{,}000\ A) = 250\ volts$$

hence, a TCL of 300 volts for waveform 4, as defined in AC 20-136 [4].

The harness-shield TCLs have been based on experience with similar-sized engines and installations. Verification that actual-shield currents (sometimes called bulk-cable currents) do not exceed these levels will be accomplished by test of an engine with typical intra-engine and engine-airframe harnesses installed, as described briefly in section 3.5.7 (Step g) and the referenced test plans.

If actual harness-shield currents are found to be higher than the proposed TCLs, the TCLs and corresponding ETDLs will be increased proportionately or a design change will be implemented to reduce the ATLs.

3.5.6 Step f - Design protection

The LTI-1000 ECS is designed to minimize the magnitudes of lightning-induced transients on the wire-harness shields and conductors, and to provide protection at the component (box) level in cases where expected transients would otherwise exceed component tolerance levels. Some of the protective measures incorporated in the LTI-1000 ECS design are listed in Table 6. The adequacy of each of those measures will be verified by the tests described in section 3.5.7 (step g).

Table 5 LTI-1000 Equipment Transient Design and Control Levels

	Equipment Interfaces					
Application	**ECU**	**Other**	**Waveform (Note 1)**	**TCL (Note 1)**	**ETDL (Note 1)**	**Remarks**
LRU connectors, pin-to-case ground	**E1, E2**	**Engine mounted accessories interfacing with ECU**	**4**	**Level 3**	**Level 4**	**Note 2**
Intra-engine harness shields	**E1, E2**	**Engine mounted accessories interfacing with ECU**	**5A**	**5 kA**	**10 kA**	**Note 3**
LRU connectors, pin-to-case ground	**E3**	**Aircraft signal interfaces**	**3B** **4**	**Level 3** **Level 3**	**Level 4** **Level 4**	**Note 2** **Note 2**
	E3	**28 VDC power**	**4**	**Level 3**	**Level 4**	**Note 4**
Engine-to-airframe	**E3**	**Airframe mounted components**	**5A**	**5 kA**	**10 kA**	**Note 3**

Table 6 - ECS Protective Measures

Protective Measure	Result
• Improved electrical bonding between accessories and engine	**Reduces potential differences**
• Shielding of all intra-engine harnesses; shields grounded at both ends	**Reduces magnetic field coupling to signal conductors to insignificant levels**
• Transient suppression diodes at ECU interfaces to sensitive circuits	**Reduces incoming transients to levels that can be tolerated by circuit board components**
• Dual-channel design and operation	**Provides a second operational channel to perform control functions in the event the first is upset or damaged**
• Isolation of electrical circuits from case ground at engine-mounted accessories	**Reduces induced currents to low levels, reducing stress at ECU interfaces**

3.5.7 Step g - Verify protection adequacy

The adequacy of the LTI-1000 ECS design to withstand lightning indirect effects will be verified by four series of tests. Two of these verify that actual transients induced in the interconnecting wiring do not exceed the established TCLs, and the other two verify that the ECU and other engine-mounted electrical components can safely tolerate the ETDL. These tests are described briefly in the following subsections. Complete descriptions are followed in the referenced test plans.

3.5.7.1 Transient control level (TCL)

3.5.7.1.1 Harness shield currents

Verification that the ECS harness-shield currents do not exceed the shield-current TCLs listed in Table 5 will be accomplished by tests of an engine with ECS components and interconnecting wire harness installed. In these tests, the simulated-lightning currents will be injected into the output shaft and allowed to exit the engine via simulated mounting struts, drains, harness shields and each of the other conductive paths listed in Table 3. These tests will be conducted on an EMI test rig, which consists of an engine case equipped with all engine-mounted accessories and suspended within a frame above a ground plane via insulating straps. This enables the actual exit paths to be simulated with metal straps, harnesses, etc. Measurements will be made of currents induced in the ECS intra-engine wiring harness, including all of its branches. These are the shield currents referred to in Table 5. The engine-airframe cable will also be represented in the test so that a measurement can be made of current in its shield. In addition, measurements will be made of currents exiting the engine via the other paths, for comparison with the original assumptions.

The ECS harness-shield current tests are described more fully in the referenced Test Plan #1.

3.5.7.1.2 Conductor voltages and currents

Actual transient voltages induced in conductors within the ECS engine harness will be determined by test of an actual intra-engine harness. In this test, the shield currents determined from the engine test of section 3.5.7.1.1. will be injected into the intra-engine and measurements will be made of the voltages induced in conductors within. This test is conducted on a bench with conductors shorted to shields at remote (accessory) ends of the shield branches so that all of the conductor voltage and current can be measured at the ECU ends. Measurements will be made of induced voltage at open, ungrounded ends of conductors extending into each branch of the cable (the open-circuit voltage, Voc) and of the current flowing in the same conductors when both ends are shorted to the shield (the short-circuit current, isc) as these are the parameters by which the TCLs are defined.

Details of the intra-engine harness test are presented in the referenced Test Plan #2.

Actual transient levels in the conductors within the engine-airframe harness will not be measured during this test, as this harness is furnished by the airframe manufacturer. The TCLs and ETDLs established for the airframe interfaces in Table 5 will become part of the engine/airframe interface specification.

3.5.7.2 Equipment transient design level (ETDL) verification

3.5.7.2.1 Damage tolerance

Verification of ECS component compliance with the ETDLs listed in Table 5 will be accomplished by pin-injection tests, in which full-scale transients defined in Table 5 and Appendix IV of AC 20-136 [4] will be injected into equipment connector-pins, between individual pins and case grounds. These tests verify ability of circuit-

board components and protective devices to tolerate the established ETDLs without damage.

Pin-injection tests will be conducted on the ECU as well as the other ECS engine-mounted accessories. In situations where these accessories also have complied with line-to-ground, high-potential (hipot) test requirements that exceed the ETDLs, the ETDL pin tests may be waived upon presentation of hipot test reports.

The pin-injection tests are conducted on the ECU in a power-on but non-operational status. Other accessories will be tested in a power-off configuration. The pin-injection tests are described in the referenced Test Plan #3.

3.5.7.2.2 System functional upset

Verification of the ECS' ability to continue to perform its intended functions during and after exposure to lightning's indirect effects will be demonstrated by a system-upset test of a complete engine-mounted ECS, powered up and operating. For this test, induced multiple-stroke and multiple-burst transients are transformer-coupled or directly injected into the harness shields while the system is operating in each operational mode. These tests will be conducted on a system installed on the same engine case that was utilized for the harness-shield current tests of section 3.5.7.1.1. The test currents will be full-threat, harness-shield ETDLs as defined in Table 5, applied in the multiple-stroke mode, with one transient corresponding to current component A, as defined in Table 5 followed by 23 transients of one fourth this amplitude, corresponding to component D/2, all within two seconds, as defined in AC 20-136 [4].

The system-upset test is described in the referenced Test Plan #4.

3.5.7.3 Sequence of verification tests

The four tests described in the preceding subsections will be conducted in the sequence shown in Figure 4, so that the results of one test are available to support the next and substantiate any design changes that might be necessitated by test results. In this way, the tests provide a building-block approach to certification, and allow each level of the protection to be validated.

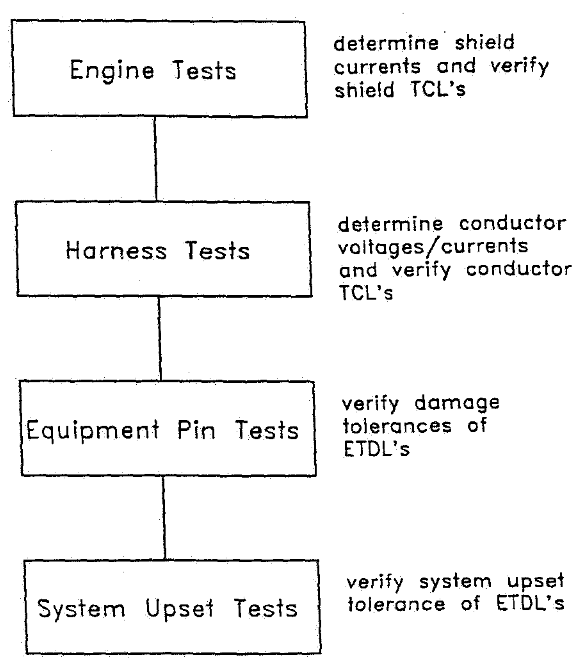

FIGURE 4 Sequence of verification tests

Test Plan References

#1. Engine-mounted harness-shield current test plan
#2. Engine-mounted harness-conductor voltage/current test plan
#3. ECS-equipment damage-tolerance test plan
#4. ECS system functional upset test plan

END OF "LTI-1000 CERTIFICATION PLAN"

4.0 EXPERIMENTAL METHODS OF ANALYSIS

4.1 AIRCRAFT/ENGINE TCL-VERIFICATION TESTS

As noted in Section 3.5.7.1 of the certification plan for the hypothetical LTI-1000 engine, the verification that TCLs associated with intra-engine cables (i.e., between engine and engine-mounted accessories) do not exceed the specified values for these circuits, is accomplished by an LTA test of an engine housing with all engine-mounted accessories and all intra-engine wiring harnesses in place. This low-level pulse test may be conducted on an engine by itself, rather than in a completely configured vehicle, because the TCLs of interest here are associated only with engine-mounted circuits. For verification of the TCLs assigned to the engine-aircraft circuits (i.e., between engine and CVU or pilot-input force transducers) a full-vehicle LTA test may be required. LTA tests should also include measurements of bulk-cable currents, currents on cable shields, magnetic fields within structures and structural IR voltages when appropriate.

4.1.1 Approach

LTA tests usually are low-level current pulse tests with the waveshapes of Component A and H as defined in FAA AC 20-136 [4] Appendix III. Other components are not used since the Components B and C produce insignificant indirect effects and the effects of Component D are exceeded by the effects of Component A. The resulting induced voltage and current transients in the aircraft wiring and harnesses will be measured and recorded by oscilloscopes located in or near the aircraft. Peak currents applied to the airframe generally can be limited to 1 kA or less to prevent any damage from occurring to the aircraft or avionic equipment. The measured data will then be extrapolated linearly to predict the actual transient levels that would appear in interconnecting wires during a full-threat, 200 kA stroke to the aircraft. An overview of the procedures and practices to conduct low-level pulse LTA tests may be found in "Lightning protection testing of full-scale aircraft to determine induced transient levels," by M.M. Dargi [6], "Lightning protection of aircraft."[7] and NASA CR-2524 "Lightning effects on the NASA F-8 digital-fly-by-wire airplane." [8] No further discussion of full-vehicle tests is provided in this paper.

4.2 ETDL VERIFICATION TESTS

In December 1989, the Radio Technical Commission for Aeronautics (RTCA) issued revision C of DO-160 Section 22, providing standard procedures for the conduct of lightning-induced transient susceptibility tests. Because of the rapid proliferation of sensitive electronics into more and more aspects of flight control, the trend toward lower operating voltages in these electronics, and the advent of "off-the-shelf" aeronautic devices intended for installation in a variety of applications, RTCA DO-160C Section 22 has been deemed inadequate. Since that time, the committees SAE AE4L and EUROCAE WG-31 SGI have been working on a revision. This will address, in greater detail, the waveforms, test levels, configuration of equipment-under-test (EUT), test procedures, measurement procedures, test equipment and safety procedures required for the conduct of ETDL verification tests for individual LRUs. Additional tests are usually necessary for verification of complete, interconnected FADEC and FBW systems.

As ETDL tests are generally bench tests performed by the equipment vendors to the specifications of the system integrator or airframe manufacturer, the success of the overall lightning protection for the entire aircraft may depend on the authenticity of the test simulation conducted by the equipment vendor. It may not be sufficient to perform ETDL tests, especially for system-functional upset, on a generic basis. It is preferable to perform ETDL analyses which relate to the actual configuration for the specific aircraft. Using DO-160 as a baseline, engineers should tailor ETDL tests to reflect actual operating loads, power- and signal-cable sizes, types and routing. Failure to do so could, at best, result in unneccessary expense and aircraft weight due to overdesign - at worst, underdesign.

4.2.1 Pin-Injection Tests

Pin-injection tests are designed to define a very specific level of damage tolerance. Depending on the type of EUT, these tests should be conducted with different methods and different pass/fail criteria.

For simple electrical/electromechanical components, such as valves, solenoids and switches, which are normally isolated from case or aircraft ground, the hipot or dielectric-withstand test is used. The EUT is unpowered and test currents are applied pin-to-case in accordance with specified ETDLs and idealized waveforms of DO-160. Figure 5a gives a typical test setup. If the EUT suffers no voltage breakdown to case, then the unit has been verified to withstand the specified damage-tolerance ETDL.

For simple electrical/electromechanical components which are normally referenced to case or local aircraft ground, a circuit-damage tolerance test is also required. In this situation, the EUT is normally powered because the follow-on currents from the power bus would accentuate any damage and make detection of potential circuit damage clearly distinguishable. Test currents are applied pin-to-case or pin-to-pin. Figure 5b illustrates a typical configuration. If no unintentional voltage breakdown to case occurs and there is no component damage, then the EUT has passed. Some equipment includes suppression devices that will intentionally shunt current to case.

For more complex electrical and electronic components -typically those containing solid-state circuitry - two possible conditions exist. When, under normal operating conditions, operating voltage constraints, impedance definitions, ground conditions and loading characteristics for the EUT are controlled by other equipment supplied by a different vendor, and the EUT manufacturer has no indication of suppression devices or filtering on interconnecting wiring, then pin tests must be performed to full specification of voltage and current.

In the second case, if loads and other operating parameters for the EUT are under the control of the EUT manufacturer, then any line-to-ground surge impedance and line-to-ground load impedance which exist in the interconnecting wiring may be used to relax test currents applied to the appropriate EUT pin. Since cable lengths and geometry play a role in surge characteristics, and they are not usually under the control of the EUT manufacturer, then relaxation of the specifications should be limited to line-to-ground transmission line impedances only - typically from full specification of 5 ohms to 50 to 100 ohms. This is usually applied only to waveforms 2 and 4, and waveform 5 if used as a pin test.

In both cases, power is applied to the unit, but loads are not interconnected. Transients are applied pin-to-case or pairs of pins-to-case under the assumption that case is power ground. Pass/fail conditions are again unintentional voltage breakdown, component damage and loss of function after the EUT is reconnected to the system. One special condition which must be considered is that testing must assess the possibility of change-of-state in the circuitry. To ensure that worst-case situations have been evaluated, circuits should be tested in both states. Because verification tests are performed under certification conditions and EUT configuration may not be altered, some developmental breadboard testing of specific circuits may be required to evaluate certain circuits in both states.

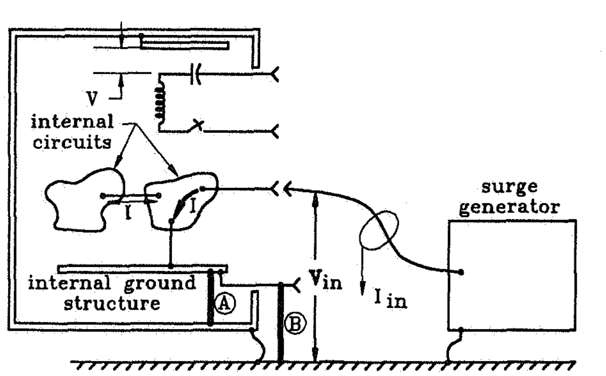

FIGURE 5a Pin-injection of an ungrounded system

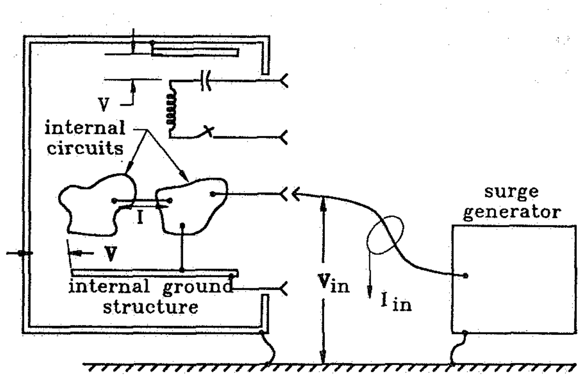

FIGURE 5b Pin-injection of a grounded system

4.2.2 Functional tests

Functional tests are designed to evaluate the LRU, its wiring harnesses and its loads as an integrated and functioning system or subsystem. DO-160 is again a minimum requirement specification designed for off-the-shelf components; when that component is integrated into a system, the ETDL verification should reflect the actual configuration of the installed system. Particular attention should be given to ensure that bench tests reflect the actual lengths, orientation and operating conditions of interconnecting wiring, such as cable routing, cable size, cable types, shielding, cable branching, actual loads or load simulation. In short, transient susceptibility should be verified to actual configuration for each and every wire, not to a generic cable-bundle specification. ETDLs should be tested *separately to each interface, not simultaneously to all interfaces,* because this would pose a much lower threat to certain LRU interfaces. For example, if 1000 amps is specified for a connector, then 1000 amps should be applied to each connector, not 1000 amps applied to a cable bundle with many connectors. The setups illustrated in DO-160 are very generic, consisting of one LRU, with one cable and one load; most actual installations are not as simple. DO-160 must be used as a baseline and *adopted to the aircraft installation.* The closer the test setup is to actual installation, the less analysis will be required to correlate the test with verification requirements. The result will be increased safety, and may also reduce the use of unnecessary suppression devices. If generic tests require that every interface withstand a specified level of threat, but a thorough simulation shows that particular connectors will be subject to lower transient levels due to their actual configuration, those connectors will require less protection.

In all such tests, the EUT must be fully functional. System responses, as seen by the pilot, are monitored for unacceptable responses per specified pass/fail criteria.

5.0 RESPONSIBILITIES

Because it is rarely practical to perform full-threat tests on fully configured aircraft, the key to successful protection will be the degree to which the system and subsystem tests simulate actual internal lightning conditions to be expected in the complete aircraft with all components interconnected and operational. These tests will depend in turn, upon the accuracy of the airframe manufacturer's or system integrator's prediction of TCLs, the thoroughness of ETDL verification as tested by the system suppliers, and the sufficiency of the margins to account for any uncertainties in these conditions. The coordination between the airframe manufacturer and system/subsystem suppliers in this process is fundamental to adequate protection.

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